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PROCESS DEVELOPMENT FOR AUTOMATED SOLAR CELL AND
MODULE PRODUCTION

Task 4: Automated Array Assembly
Quarterly Report No. 3

By
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July 13, 1979

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U.S. Department of Energy

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PROCESS DEVELOPMENT FOR AUTOMATED SOLAR CELL AND MODULE PRODUCTION

TASK 4: AUTOMATED ARRAY ASSEMBLY

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ABSTRACT

The objective of this program is to develop process and handling technology required to allow large volume, low cost terrestrial solar array production. Emphasis has been placed on module lay-up and interconnect and edge sealing.

During this reporting period, progress has been directed toward automated interconnection and lay-up of solar modules using a Unimate model 2000B industrial robot. A study of interconnect bond methods lead to the decision that induction heating would be most applicable to robot operation. The design approach for the interconnect and lay-up station involves a cell preparation sub-station that will unload the cells from cassettes, orient them optically and position an interconnect for bonding to the cell. At that point, the robot arm with a bonding head, will solder the lead, then place the cell into the array configuration, and solder it to the adjacent cell. The robot has been programmed to pick and place 3 inch diameter cells into a 12" X 16" array with an average time of 6 seconds per cell. This can be reduced by optimizing the program and a target rate of 6 - 12 seconds per cell was set for placement and interconnection.

Edge sealant compatibility studies continue. Hot melt techniques have been demonstrated by adhering the edge frame to several 1' X 4' modules using an off-the-shelf hand held hot melt gun.

TABLE OF CONTENTS

<u>Section</u>	<u>Title</u>	<u>Page</u>
1.0	INTRODUCTION	1
2.0	TECHNICAL DISCUSSION	2
2.1	Bond Methods	2
2.1.1	Resistance Heating	2
2.1.2	Ultrasonic Bonding	2
2.1.3	Laser Bonding	3
2.1.4	Induction Heating	3
2.2	Interconnect Hardware	4
2.3	Metalization Pattern Recognition and Cell Orientation Techniques	4 & 5
2.4	End Effector Development	6
2.4.1	End Effector Design Criteria	6
2.4.2	Options	7 & 8
2.4.3	Cell Handling	9
	FIGURE 1: Preparation Station & Panel Lay-up	10
	FIGURE 2: Vacuum Pick-up of Solar Cell	11
	FIGURE 3: Unimate Handling Cells	12
	FIGURE 4: Placement of Solar Cell Into Array	13
2.5	Edge Sealing	14 & 15
	FIGURE 5: Application of Edge Sealant	16
3.0	CONCLUSIONS	17

1.0 INTRODUCTION

The scope of work under this contract involves analysis, assessment and development of techniques for emplacement and interconnection of solar cells and application of edge sealant materials to encapsulated modules. The diversity of solar cell shapes, sizes and metalization patterns requires a versatile interconnection system, unless or until an optimum, industry wide standard emerges. Programmable automation provides this versatility in an off-the-shelf form. Efforts are being directed toward utilizing this potential by developing cell handling and bonding techniques compatible with this type of automation. Success in this area will not only provide technology for interim production lines, but could form an experimental basis for the determination of an optimal standard.

2.0 TECHNICAL DISCUSSION

2.1 Bond Methods

Several bonding methods were investigated during the past period. The following sections discuss the trade-offs involved with each method.

2.1.1 Resistance Heating

Conventional resistance heating (e.g. soldering iron) has the advantages of being both inexpensive and fully developed. It requires no bulky power supplies or signal generators and is easily adapted to an end effector. However, it is far too slow (5 - 10 sec. per connection) for production line assembly. Because of its simplicity, though, it will probably be used for preliminary feasibility demonstrations of robot end effector designs where speed is not important. This will allow parallel development of a more sophisticated bonding method.

2.1.2 Ultrasonic Bonding

This method shows great promise for interconnection of solar cells. It uses a signal generator which can be remotely located and only the lightweight transducer need be mounted on the end effector. Another advantage is that the bond is a direct metal-to-metal weld which requires no solder or flux and effectively bonds both aluminum and silver; two metalization systems used. The bond time is very fast (<0.5 sec.) and energy consumption is low since the materials to be joined are bonded directly and surrounding areas remain cool. Unfortunately, our investigation shows that near optical-bench stability is required to assure reproducible bonds. Vibrations from roof-mounted air conditioners and closing doors were sufficient to degrade bond quality. Since these are several orders of magnitude lower than vibrations at the end of the robot arm, this method appears unusable at present.

2.1.3 Laser Bonding

Laser cutting and welding are becoming quite popular in industry and there are many off-the-shelf units that would be directly applicable. Lasers have the advantages of being very fast and extremely versatile in terms of pulse duration and focusing. This allows the laser to be "tuned" for either welding or soldering. Although welding does away with both solder and flux, soldering is expected to be better for bonding leads to solar cells. Industrial lasers operate in the infrared region and all of the materials presently under consideration for leads and metalization patterns (Al, Ag, Cu, Sn) are highly reflective to IR. The very high initial pulse necessary to overcome reflective effects and weld the lead material ($\approx 100\text{w}$) could simply vaporize it and damage the cell. Laser bonding holds great promise for industrial scale production but has several drawbacks that make it unsuitable for prototype development with the Unimate robot. Although the beam can be positioned almost anywhere (through appropriate optics) once in place it must remain fixed and the array moved under the beam. An X-Y beam moving system is available, but it is very expensive (150K) and moves only 16" X 16".

2.1.4 Induction Heating

This fast bonding method has advantages similar to ultrasonic bonding in that the power supply can be remotely located with only the coils and concentrator (bonding head) on the robot. Additionally, since heat is produced by inducing eddy currents in the material rather than bonding by direct mechanical vibration, the head need only be brought into close proximity to the material being bonded, rather than requiring a rigid, vibration free, accurately positioned contact. All that is required is a slight pressure on the lead to ensure contact during bonding.

Since it is a zone heating system, it doesn't have the precise area control of a laser or ultrasonics; hence it would be used to solder rather than weld, requiring the application of solder. Other than that, induction heating seems to have the advantages of ultrasonic bonding without the rigid requirements. We have therefore, decided to pursue induction heating over the next period for prototype development.

2.2 Interconnect Hardware

Several interconnect hardware configurations were studied. Ribbons of various alloys are currently being used by module manufacturers. Expanded metal mesh is also being used which has the advantage of built-in stress relief, and could be formed into a ribbon. Pre-formed interconnects are also used, but severely restrict the versatility of the system. Ribbon interconnects were chosen primarily for their flexibility as ribbon materials can form any length of interconnect. Either a short tab or a lead across the entire diameter of the cell could be made at the same station. The ribbons come in a variety of alloys and dimensions and the rolls they come on can easily be incorporated into an automated interconnection station.

2.3 Metalization Pattern Recognition And Cell Orientation Techniques

Preliminary conceptual design has begun on the metalization recognition and cell orientation for interconnection. The cheapest and fastest method would probably be a mechanical alignment on the flat. Many round wafers for solar cells are made on the same production lines as those for the micro-circuit industry. These have a flat machined onto the edge which the IC manufacturers use to align the wafer for their many precision operations. Solar cells do not require

this precision and designing orienting machinery around the flat increases the production cost of the wafer through both the extra time required to machine the flat and in material loss.* Many manufacturers also produce square and hexagonal cells which have an inherent flat side and could use mechanical alignment. An orientation system, however, should be able to accept cells of any configuration. Barring the guaranty of a flat side, orientation can be achieved by optical methods.

One such method involves the use of a negative of the grid mask to create a moiré fringe pattern with the cell grid. The object is to maximize the signal generated from the reflection of the cell through the negative screen. The basic components involved are the:

- (1) Negative Image
- (2) Lens
- (3) Photodiode
- (4) Amplifier

This method gives good continuous feedback and can handle 1° orientation relatively well. This is a simple and inexpensive optical orientation method, but more flexible and accurate methods are possible.

Pattern recognition can be accomplished using a laser to scan the metalization pattern and detect the reflection from the grid lines with a photodiode, amplifier and comparator. Using beam splitting techniques to get 2 or 3 beams, the alignment can be determined and corrected by ascertaining

*This is more than just scrap loss since the machined-off portion is active cell area. Although it is only 0.8% of the total cell area, this is equivalent to 24 cells/hr. on a line producing 3000 cell/hr.

the period and phase difference between the scans of the grid lines. This is a fast, accurate and versatile method. By incorporating a stepper or DC motor into the end effector rotation of the cell could be accomplished while the arm is in transit with a minimum amount of hardware on the robot arm itself. The circuits could easily be programmed to recognize and orient any type of cell or pattern. The negative image method has been chosen as an adequate and inexpensive method to orient the cells for demonstration purposes. Laser scanning techniques would probably be implemented for production situations.

2.4 End Effector Development

The conceptual design and development of cell handling end effectors has been preceded by an analysis of the constraints and design criteria for the end effector and the options available for the sequence of steps and techniques for lay-up and interconnection of a module.

2.4.1 End Effector Design Criteria

The constraints and design criteria considered were:

- (1) Versatility
- (2) Speed
- (3) Accuracy
- (4) Simplicity
- (5) Light weight
- (6) Reliability
- (7) Cost

The end effector should be able to handle the various sizes, shapes and metalization patterns of cells and be able to place and interconnect them into whatever module size and series/

parallel configuration desired. Proposals for hard automation assembly machines are in the range of 5 seconds/cell. If the versatility of programmable off-the-shelf hardware is desired, a sacrifice in speed must be tolerated. A target rate was set at 6 - 12 seconds per cell for development and demonstration.

More detailed studies of the cell placement tolerance requirements must be performed. These will involve geometrical analysis, cost and materials trade-offs. Surveys will be made of the tolerance requirements for various manufacturer's modules. Cell placement tolerances are expected to be different for square and round cells. Simplicity of the end effector will reduce the cost and increase reliability which should put the output in the 95% range with overall system cost directed towards the LSA goals. A lightweight end effector will reduce the inertial effects to the robot arm, and keep it moving at the maximum speed.

2.4.2 Options

The step sequence options for lay-up and interconnection include placement and interconnection of the cells into a ribbon or other convenient sub-unit configuration. The sub-units would then be placed and connected into the module configuration (as a hexagonally close packed module for instance). Another option would be to place the cells directly into the module configuration, place an interconnect, place a cell and iterate until the module was complete. Then a reflow scheme would finish the interconnection. A third alternative would place a cell and electrically bond it to the adjacent cell in one operation. The first option would be fast, as the robot would be placing more than one cell at a time. However, another robot (or piece of dedicated hard automation equipment) would be needed to form the sub unit. The versatility

would be severely restricted as the end effector would be designed to pick and place a specific sub-unit. Variations in size and shape of the cells would alter the relative position of the cell's center increasing the complexity of the tool or requiring a separate one for each shape variation. Placement of the cells and interconnect hardware alternately gives greater versatility but would be slow and require a reflow step. The pick, place and interconnect configuration offers more speed than the placement of cells and interconnects separately.

Options in cell handling techniques include mechanical and vacuum pick-up. Vacuum handling offers versatility, using a suction cup which can pick up any size and shape cell. A mechanical gripper would be complex if it were to accomodate the range of cell types. A vacuum cup is easy to control through the use of the robot memory and controls. It can be bellows shaped (and therefore compliant) to cushion the cell and reduce damage during handling and placement. Air ejectors can also be used to create the vacuum from compressed air.

An important trade-off to consider is the amount of work to be performed by the robot itself versus a preparation station or another robot. A preparation station could orient the cell, attach interconnect hardware and flip the cell in preparation for the robot whose job becomes: pick and place and final connection. Another approach would be to have the robot pick up the cell, orient it, attach hardware, flip and place it, and complete the interconnection. This would involve a rather elaborate end effector and probably a longer cycle time. However, end effector design is restricted by the limited maximum load of the robot (25 lbs. at maximum speed, 75 lbs. maximum at reduced speed) which precludes very elaborate designs.

The design we have chosen to pursue over the next period falls between these two extremes (see FIGURE 1).

In this scheme, a commercial cassette unloader presents the cell to an orientation station. Here, a vacuum chuck attaches to the underside of the cell then an optical feedback arrangement orients the cell via a positioning motor attached to the vacuum chuck.

Once correctly oriented, a small dab of solder paste is applied to the contact pad on the metalized surface. The lead material is fed out from the supply spool until it just covers the contact pad. A cutter/crimper cuts the lead to the correct length while simultaneously forming stress relief bends in the material. This also holds the lead immobile while the robot bonds the lead to the cell. The lead is released and a dab of solder paste is applied to the free end. The robot end effector, which will consist of a vacuum pick-up and a soldering head, picks up the cell and places it in the matrix over the exposed lead of the previous cell. It then moves its soldering head to the opposite end of the cell (either by rotating or translating) and bonds it to the previous cell's lead.

This system will be designed so it can easily be modified to accomodate multiple leads of variable length and relative position, providing versatility with respect to cell size and metalization patterns.

2.4.3 Cell Handling

The Unimate robot has been successfully programmed to place 3" diameter cells into a 12" X 16" array using a single vacuum cup. FIGURES 2, 3 & 4, show the robot in the process of picking the cells from a simulated preparation station and placing them into the array. The average placement time was

FIGURE 1
PREPARATION STATION AND PANEL LAY-UP

FIGURE 2
VACUUM PICK-UP OF SOLAR CELL

FIGURE 3
UNIMATE HANDLING CELLS

FIGURE 4
PLACEMENT OF SOLAR CELL INTO ARRAY

6 seconds per cell and it is believed that this can be improved with path and programming optimizations.

The Unimate tester model 5023A has been received and is being used for fine tuning robot performance. The tester allows reading of the memory, manipulation of single motions individually and facilitates maintenance and trouble-shooting. A sequence controller has been ordered that will enable the robot to switch into various base routines that contain instructions for small repetitive operations such as picking up cells at the same location or rejecting, rather than placing a cell. It allows a "decision" to be made externally, by a cell tester for instance, with the robot responding to the external signal and switching into a base routine. A signal can come from the main program (called a sub-routine) so repetitive operations need be programmed only once and repeated when signaled from the sub-routines. The sequencer is programmed for two base routines and two sub-routines but is versatile and can be programmed to meet system needs.

2.5 Edge Sealing

Edge sealant/encapsulant compatibility testing has begun with test modules. The variety of encapsulant materials led to the selection of four module designs to cover the range of possible materials.

The modules are:

<u>MODULE NO.</u>	<u>MATERIALS</u>
1	Glass, PVB, Tedlar
2	Acrylic, EVA, GRC
3	Acrylic, Silicon, Wood
4	Tedlar, EVA, Aluminum Foil

These test modules have been fabricated and the edge sealant selected for testing, HB Fuller 1081, has been applied using

off-the-shelf hot melt application equipment. The modules are undergoing exposure in an Atlas Weather-Ometer model XW-1870 with carbon arc UV source and water spray. Currently, a cycle of 102 minutes of arc only and 18 minutes of arc and spray is being used. HB Fuller 1081 hot melt was successfully used to apply the frames and edge seal to two 1' X 4' modules. The sealant was applied into the channel of the frame with a Hardman Polymeric sealant applicator (PSA) model 240, shown in FIGURE 5. A specially designed nozzle was used to get material distribution over the sides and bottom of the channel, leaving a slight space for the module to be inserted and reducing the need for the viscous material to flow out along the sides of the module. Open times were sufficient to allow good flow characteristics and adhesion, even though the sealant was applied with a hand held gun and consequently was slower than possible with automation. There appears to be no need to preheat the aluminum frames. Plexiglas frames were constructed and used in some of the framing experiments to verify that no bubbles were entrapped. One of the 1' X 4' framed modules will be placed outdoors for exposure testing.

Another material that will be investigated for edge sealing potential is ethylene propylene rubber. It has been used for sealing automobile windshields with good results and shows promise as an edge gasket type of seal.

FIGURE 5
APPLICATION OF EDGE SEALANT

3.0

CONCLUSIONS

At this stage, soldering by induction heating is the bond method most applicable for use with an industrial robot. A fast and versatile approach using this bond method and a Unimate 2000B robot would incorporate ribbon interconnects formed, cut and held by a preparation station which orients the cell while the previous cell is being placed and bonded into the array by the robot.

Optical orientation of the cell using the contact pad would eliminate dependance on the "flat" of the wafer and add versatility with respect to cell shapes and metalization patterns.

It is possible to teach a robot to pick up and place solar cells into an array and no problems are foreseen with the implementation of an interconnect scheme placing cells at a rate of 6 - 12 seconds per cell.

Hot melt adhesives can be used to apply frames to modules with off-the-shelf hand-held equipment.